Wavefront Sensor Design based on a Micro-Mirror Array for a High Dynamic Range Measurement at a High Lateral Resolution

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1 Introduction

Optical testing is confronted with the challenge of a flexible testing of precision aspheres. This challenge can be faced by test equipment with a high measurement range at a high resolution, i.e. a high dynamic range. Compared to other sensor types for optical testing the Shack-Hartmann sensor (SHS) features a high dynamic range. In SHS the measurement range is limited due to the fact that all measurement points are detected simultaneously by an imaging device and the signals must be separable - thus the dynamic range is defined by the number of micro-lenses and the resolution of the imaging sensor. There are several approaches to enhance the dynamic range such as image processing approaches, e.g. spot tracking and unwrap algorithms [1] - or the use of additional optical elements, e.g. masks [2,3] or adaptive diffractive micro lenses as in the adaptive Shack-Hartman sensor [4]. But despite these approaches the contradiction between dynamic range and lateral resolution couldn't be resolved - a flexible wavefront testing of technically relevant aspheres is still restricted.

In this paper an approach of wavefront sensing is proposed in order to increase the dynamic range and the lateral resolution at the same time. The basic idea is to select and thereby encode single sub-apertures of the wavefront under test and to measure their propagation direction consecutively in a scanning procedure. In difference to the LCD based approach described in [3], here the selection of the sub-apertures is performed by a digital micro-mirror array (DMD). The use of the DMD promises a high reflectivity and lateral resolution as well as a very fast scanning ability. But there are specific challenges as the diffraction effects caused by the small dimensions of the array and the angular stability of the signal which will be addressed in this paper.

2 Set-up of the DMD-based wavefront sensor

The general set-up of the proposed sensor is depicted in Fig. 1. The wavefront to be measured is generated by a point light source - here realized by a fiber coupled laser diode (1, 2) - which is collimated by the lens under test (3). The wavefront to be measured (4) is imaged by a telescope in 4f-arrangement (5) onto a DMD (7). Form here on the evaluation of the wavefront differs from SHS. The micro-mirrors of the DMD can be addressed individually and can take two different tilt positions. By means of the DMD and its micro-mirrors any sub aperture can be selected and reflected towards the evaluation unit while the rest of the wavefront is reflected towards an absorber (6). The evaluation is performed by the same principle as in SHS, but with a single focusing lens (8). In the back focal plane of the lens the propagation direction of the selected sub aperture is transduced into a position which is detected by position sensor (9).

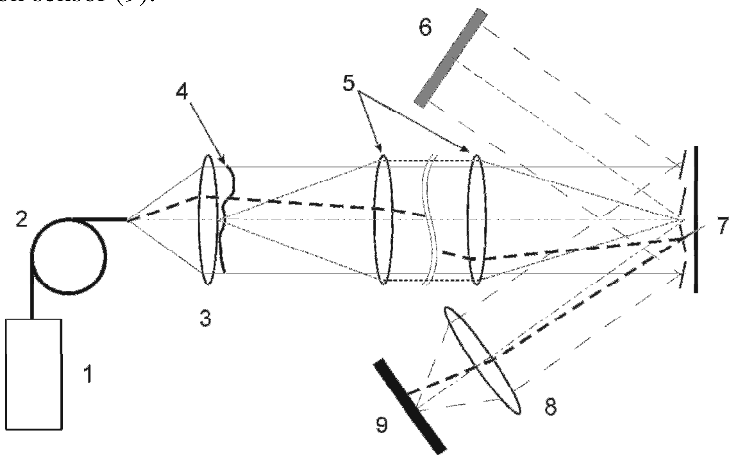

Fig. 1. Schematic sketch of the sensor set-up, 1: light source, 2: optical fiber, 3: lens under test, 4: aberrated wavefront, 5: imaging telescope, 6: absorber, 7: micro mirror array, 8: focusing optic, 9: position sensor

For the measurement of the whole wavefront all sub apertures are scanned consecutively. By this scanning procedure each measurement point can be evaluated with the whole dynamic range of the detector, whereas in SHS the dynamic range of the detector was used for the evaluation of all measurement points in parallel. Thus, the measurement range can be increased while accuracy is not reduced. Here a micro-mirror device SXGA+ Discovery™ 3000 by Texas Instruments is used which counts more than thousand per thousand mirrors (see Table 1), determining the maximum number of scanned points to one over thousand of the lateral measurement range. Disadvantageous are the small dimensions of the single micro mirrors of the DMD that lead to diffraction effects.

Table 1. Technical data of the Texas Instruments DMD SXGA+ Discovery™ 3000 [5]

Number of micro mirrors	1400 x 1050
Tilt angle	±12°
Pitch (*a*) / mirror edge length (*b*)	13.68 µm / ~12.61 µm

3 Description of the diffraction effects

The microstructures of the TI DMD are associated with a Fresnel number of F ~ 3 10^{-3} while using light within the visible spectrum. Therefore diffraction in the Fraunhofer region can be expected.

The series of mirrors can be considered as a reflective blazed grating consisting of *N* tilted mirrors of the width *b* and the grating constant *a*. In case of the Texas Instruments SXGA+ DMD™ the blaze angle α is 12° and incident light will be reflected at $\beta = 2\ \alpha = 24°$.

To perform a measurement first all micro mirrors are tilted by $\alpha = +12°$ to direct the light onto the absorber. The centre of the diffraction pattern can be observed at $\beta = +24°$. The measurement signal is then generated by tilting a certain or more mirrors to $\alpha = -12°$, its centre will appear at $\beta = -24°$. A mathematic description to calculate the intensity profile $I(\theta)$ on the screen can be expressed as a product of two functions (see Eq. 1).

$$I(\theta) = I_{Grating} \cdot I_{Signal} \tag{1}$$

The first function $I_{Grating}$ considers the periodicity of the micro mirror array and defines the positions of the diffraction peaks (see Eq. 2).

$$I_{Grating}(u) = N^2 \cdot \frac{\sin^2\left(\frac{Nau}{2}\right)}{\sin^2\left(\frac{au}{2}\right)} \tag{2}$$

The second function I_{Signal} is the intensity distribution of a single mirror reflecting light onto the evaluation unit. Its intensity distribution is operating as an envelope of $I_{Grating}$ (see Eq. 3).

$$I_{Signal}(u) = b^2 \cdot \frac{\sin^2\left(\frac{b}{2}(u - k\sin\beta)\right)}{\left(\frac{b}{2}(u - k\sin\beta)\right)^2} \tag{3}$$

Finally, the variable u has to be substituted by the expression to find the Intensity $I(\theta)$ (see Eq. 4).

$$u(\theta) = k\sin(\theta) = \frac{2\pi}{\lambda}\sin(\theta) \tag{4}$$

For a plane monochromatic wave with a wavelength of λ = 712 nm incidenting perpendicular and the geometric specifications of the DMD as listed in Table 1, the intensity distribution can be calculated as displayed in Fig. 2.

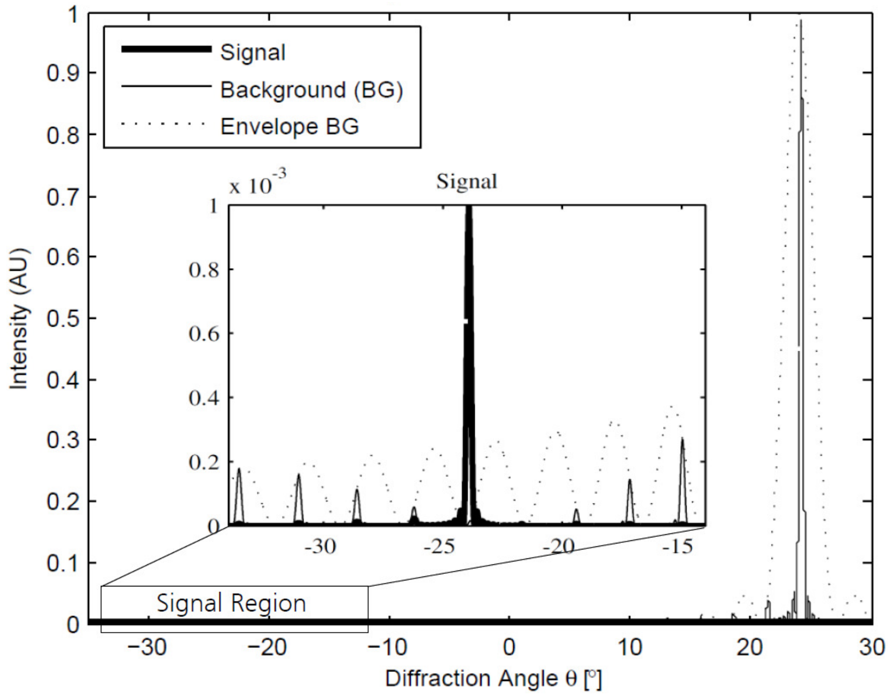

Fig. 2. Intensity profile of the reflected light for an illuminated DMD with an incident angle of 0° at a wavelength of λ = 712 nm and a signal generated by a super mirror of 3 x 3 mirrors

The wavelength is chosen in that way that the intensity of the grating $I_{Grating}$ reaches a minimum in the region of the signal since it represents an unwanted background signal. In Fig. 2 the intensity of the signal I_{Signal} was divided by 10,000 in order to take into account the smaller amount of light reflected by the mirrors contributing to the signal compared to the mirrors contributing to the background $I_{Grating}$.

4 Angular stability of the micro-mirror signal

Besides the consideration of the diffraction effects another important characteristic when using a DMD in the proposed set-up is the stability of the tilt angle of the mirrors. In order to determine the angular stability of the signal a high resolution measurement of a signal of 3 x 3 mirrors was conducted with a set-up similar to Fig. 1. The light of a fiber coupled laser diode with a wavelength of λ = 683.9 nm was collimated and directed on the DMD and reflected by the mirrors towards the evaluation unit. The focusing lens had a focal length of f = 60 mm and the position sensor was a 2D-position sensitive diode (PSD) with a sensitive area of 4 x 4 mm^2. The results are displayed in Fig. 3.

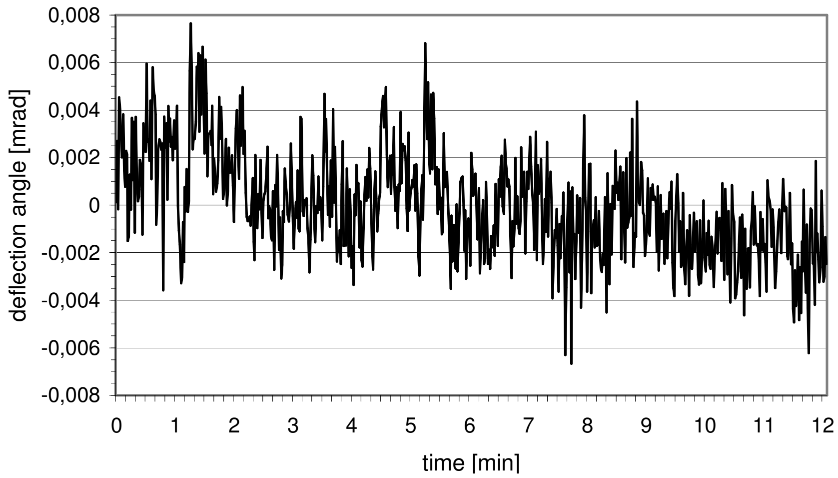

Fig. 3. Stability of the signal of 3 x 3 micro mirrors

The mirrors reflecting the signal were tilted with a frequency of 5 Hz and while tilting the position values were logged and the correspondent deflection angles were calculated. Each measurement point in Fig. 3 represents an average of 10 of values. The angle was logged over a period of more than 12 minutes in order to ensure that the drift of the system could be neglected during longer measurements. The stability of the signal had a reproducibility of s = 2.21 µrad.

5 Conclusion and outlook

The proposed wavefront sensor design based on a DMD promises to give a high lateral resolution at a high dynamic range. The diffraction effects that result from the small structures of the DMD can be reduced by the use of an appropriate wavelength. The angular stability of the signal showed to be applicable for a high resolution wavefront measurement.

Future work will mainly address the specific challenges that result from the possible high measurement range of up to 10°, such as errors that might be generated in the imaging telescope or in the focusing optic at higher field angles.

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7 References

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